

OBSERVATIONS OF ANOMALOUS X-RAY PULSARS

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ABSTRACT. We review recent results obtained from observations of Anomalous X-ray Pulsars at different wavelengths (X-rays, Optical, IR and Radio) with particular emphasis on results obtained by *BeppoSAX*. Proposed models for AXPs are briefly presented and discussed in the light of these results.

1. Introduction

Coherent X-ray pulsations from 1E 2259+586 were discovered at the end of seventies. Only few years ago it was recognized however that a number of X-ray pulsators, including 1E 2259+586, possess peculiar properties which are very much at variance with those of known accreting pulsars in X-ray binaries. These objects, initially suggested as a homogeneous new class of pulsators (Mereghetti & Stella 1995; van Paradijs et al. 1995), have been named in different ways, reflecting our ignorance of their nature: Very Low Mass X-ray Pulsars, Braking Pulsars, 6 s Pulsars, Anomalous X-ray Pulsars. The latter designation (AXPs) has become the most popular and will be used hereafter.

The nature of AXPs is one of the most challenging unsolved problems of Galactic high energy astrophysics. Over the last few years there has been a remarkable observational and theoretical effort to unveil their nature. Although we can be reasonably confident that AXPs are magnetic rotating neutron stars (NSs), their energy production mechanism is still uncertain; it is also unclear whether they are solitary objects or are in binary systems with very low mass companion. As a consequence, different production mechanisms for the observed X-ray emission have been proposed, involving either accretion or the dissipation of magnetic energy.

The properties that distinguish AXPs from known magnetic ($\geq 10^{12}$ G) accreting X-ray pulsars found in High and Low Mass X-Ray Binaries (HMXBs and LMXBs) are the following:

- spin periods in a narrow range (~ 6 – 12 s) compared with the much broader distribution ($0.069 - \sim 10^4$ s) observed in HMXRB pulsars;
- no conspicuous optical counterparts (see Section 6), with upper limits which rule out the presence of massive companions, like OB (super)giants or Be stars;

Tab. 1 - Anomalous X-ray Pulsars (AXPs)

SOURCE	P (s)	\dot{P} (s s ⁻¹)	SNR d (kpc)/age (kyr)	SPECTRUM kT _{BB} (keV)/ α_{ph}
1E 1048.1-5937	6.45	(1.5-4)×10 ⁻¹¹	—	BB+PL [3]
	[1]	[2,3]	~5 / —	~0.64 / ~2.5
1E 2259+586	6.98	~5×10 ⁻¹³	G109.1-0.1 [7,8,9]	BB+PL [9]
	[4]	[5,6]	4-5.6 / 3-20	~0.44 / ~3.9
4U 0142+614	8.69	~2×10 ⁻¹²	—	BB+PL [11,12]
	[10]	[11]	~1-2 / —	~0.38 / ~3.9
RXSJ170849-4009	11.00	2×10 ⁻¹¹	—	BB+PL [13,14]
	[13]	[15]	~10 / —	0.45 / 2.6
1E 1841-045	11.77	4.1×10 ⁻¹¹	Kes 73 [18,19]	PL [20]
	[16]	[17]	6-7.5 / ≲ 3	— / ~3.4
<i>AX J1844-0258</i>	6.97	—	G29.6+0.1 [22]	BB [21]
(candidate)	[21]		≤15 / <8	~0.7 keV / —

[1] Seward et al. 1986; [2] Mereghetti 1995; [3] Oosterbroek et al. 1998; [4] Fahlman & Gregory 1981; [5] Baykal & Swank 1996; [6] Kaspi et al. 1999; [7] Hughes et al. 1984; [8] Rho & Petre 1997; [9] Parmar et al. 1998; [10] Israel et al. 1994; [11] Israel et al. 1999a; [12] White et al. 1996; [13] Sugizaki et al. 1997; [14] Israel et al. 2001a, [15] Israel et al. 1999b; [16] Vasisht & Gotthelf 1997; [17] Gotthelf et al. 1999; [18] Sanbonmatsu & Helfand 1992; [19] Helfand et al. 1994; [20] Gotthelf & Vasisht 1997; [21] Torii et al. 1998;

- very soft and absorbed X-ray spectra: a black body with characteristic temperature in the 0.4–0.6 keV range and a steep power-law with photon index in the 2.5–4 interval (suggesting that perhaps a large part of the total luminosity is hidden in the EUV band);
- relatively low X-ray luminosity ($\sim 10^{34}$ – 10^{36} erg s⁻¹) compared with that of HMXB pulsars;
- relatively low flux variability on timescales from hours to years;
- relatively stable spin period evolution, with long term spin-down trend (see Section 5);
- a very flat distribution in the Galactic plane and three clear associations with supernova remnants (SNRs; suggesting a young population).

There are currently (February 2001) five ascertained members of the AXP class (see Table 1) plus one likely candidate. This review, after a brief presentation of theoretical models (Section 2), concentrates on the recent results inferred from observations of AXPs at different wavelengths (X-rays, Section 4 and 5; optical and IR, Section 6; radio, Section 7). The implications of these results for the proposed theoretical models are briefly discussed.

2. Theoretical Models

Theoretical models for AXPs can be classified into two main classes depending on the mechanism that is supposed to power their X-ray emission: accretion or magnetic field decay. The former class includes both isolated NSs and NSs in binary systems.

Accretion from matter in an overdense region was first proposed for 4U 0142+614 based on its apparent association with a molecular cloud. However this would imply that AXPs move at low velocities in the ambient medium (Israel et al. 1994). Mereghetti & Stella (1995) proposed that AXPs form an homogeneous subclass of accreting neutron stars, perhaps members of very low mass X-ray binaries (VLMXBs), which are characterized by lower luminosities and higher magnetic fields ($B \sim 10^{11}$ G) than accreting neutron stars in classical LMXBs. On the other hand, Van Paradijs et al. (1995) proposed that AXPs are the result of a common envelope and spiral-in evolution of a neutron star and its massive companion. This ends up in the complete disruption of the companion star after the so-called Thorne-Zytkov stage. Based on the AXPs-SNRs association, Chatterjee et al. (2000) and Perna et al. (2000), proposed instead that AXPs accrete from a fossil disk made of matter falling back onto the neutron star after its birth. Alpar (2000) proposed that AXPs are NSs accreting from the debris of their SNRs, in a phase following the SGR stage, or, alternatively, NSs accreting from a companion star in a rare path of LMXB evolution. In these scenarios the P/\dot{P} does not provide a reliable good estimator of the pulsar age; rather it should represent an asymptotic value approached by the pulsar. The equilibrium period should depend on the trapped angular momentum in the residual accreting matter (Alpar 2000). In the accretion scenario the narrow period distribution of AXPs can be accounted for by either limiting the magnetic field of the NS and strength of the propeller wind emission (Marsden et al. 1999) or using ADAF models and an appropriate distribution of magnetic field, initial spin and accretion disk mass (Chatterjee & Hernquist 2000).

Finally, Thompson & Duncan (1993, 1996) proposed that AXPs are “magnetars”, isolated neutron stars with a super-strong magnetic field ($\sim 10^{14-16}$ G; for a review see also Thompson, this book). Magnetars were originally proposed to explain the properties of soft γ -ray repeaters. These were later determined to exhibit pulse periods (8.05 s, 7.5 s and 5.16 s in SGR 0526-66, SGR 1806-20 and SGR 1900+14, respectively) and period derivatives similar to those of AXPs (Kouveliotou et al. 1998; Hurley et al. 1999). If this connection proved correct, AXPs might be some sort of quiescent analogous of soft γ -ray repeaters. In the framework of the magnetar model, Colpi et al. (2000) showed that it is possible to account for the narrow period distribution of AXPs if the initial magnetic field (in the 10^{15} – 10^{16} G range) of magnetars decays significantly on a timescale of the order of 10^4 years.

3. The AXP sample

Table 1 lists the main characteristics of the five X-ray pulsars which form the AXP class. The new AXP candidate, AX J1844-0258, is also included.

Recently a possible connection of AXPs with Soft γ -Repeater (SGRs, for a review see Kouveliotou, this book) has been proposed (Kouveliotou et al. 1998, 1999; Hurley et al. 1999); this builds on several observational similarities, such as the range of spin periods, their derivatives, and the possible association with SNRs. In the case of SGRs large offsets from the SNR centers were measured which might imply that AXPs may eventually evolve into SGRs as they age and move away from the SNR centre (Gaensler 2000). This would require a difference of 10–100 kyr in the age of AXPs and SGRs;

therefore it would be difficult to explain, in the light of the inferred period derivatives, the similarity of periods. We also note that a 226 ms radio pulsar has been recently discovered in the SNR previously associated with the Soft γ -Repeater SGR 1900+14 (Lorimer & Xilouris 2000). Although it is unclear which of the two objects (if any) is associated to the SNR, a recent reanalysis of the distance indicators (Case & Bhattacharya 1998) places the SNR at 10 ± 3 kpc, consistent with the position of the newly discovered radio pulsar. The alternative possibility is that SGRs are born with a different velocity distribution than AXPs and, therefore, the two classes cannot be drawn from the same parent population. The AXPs-SGRs connection is still an open issue.

4. The *BeppoSAX* view

Observations by different X-ray satellites have often been used to check for the presence of spectral and flux variations in AXPs. These, however, are affected by the uncertainties introduced by comparing the results of different instruments covering different energy ranges, etc. The *BeppoSAX* satellite, with a coherent set of instruments covering the 0.1–10 keV range with spectral resolution of 3–10, observed the whole sample of AXPs. Spectral results from *BeppoSAX* observations have already been reported for three AXPs, 1E 2259+586 (Parmar et al. 1998), 1E 1048.1–5937 (Oosterbroek et al. 1998), and 4U 0142+614 (Israel et al. 1999). In the following we will report on the spectral and timing properties of another AXPs, 1RXS J170849–400910 (Israel et al. 2001a), observed by *BeppoSAX* in March–April 1999. The *BeppoSAX* observation of 1E 1841–045 is not included in this report due to strong contamination from the SNR Kes 73 (timing results have been reported by Gotthelf et al. 1999). The candidate AXP AX J1844–0258 has not yet been observed by *BeppoSAX*.

The relatively bright source 1RXS J170849–400910 was discovered by ROSAT at the beginning of its mission; however only in 1997 this source attracted much attention because of the discovery of ~ 11 s pulsations with ASCA (Sugizaki et al. 1997). Based on the pulse period and unusually soft X-ray spectrum the source was tentatively classified as a candidate AXP. This interpretation was confirmed thanks to ROSAT HRI observations which provided the first measurement of the period derivative $\dot{P} \sim 2 \times 10^{-11} \text{ s s}^{-1}$ and a more accurate X-ray position from which it was possible, through optical imaging, to confidently exclude the presence of a massive companion star (Israel et al. 1999b). 1RXS J170849–400910 has been monitored with the *RossXTE* since 1998; a sudden spin-up event, suggestive of a “glitch” from a highly magnetised NS, was recorded in September 1999 (Kaspi et al. 2000a; see also Section 5).

BeppoSAX observed this source on 31 March – 1 April 1999 with the Narrow field Instruments: the Low-Energy Concentrator Spectrometer (LECS; 0.1–10 keV; Parmar et al. 1997; 26 ks effective exposure time) and the Medium-Energy Concentrator Spectrometer (MECS; 1.3–10 keV; Boella et al. 1997; 52 ks effective exposure time). A simple power-law model (as well as any other single component model) did not fit well the data (χ^2 of 1.42 for 199 degrees of freedom). A better fit (see right panel of Figure 1) was obtained including a soft thermal component in analogy with similar results obtained for other AXPs (χ^2 of 1.12 for 197 degrees of freedom). The best fit was obtained for an absorbed, $N_H = (1.46 \pm 0.02) \times 10^{22} \text{ cm}^{-2}$, power-law with photon index 2.6 ± 0.2 and

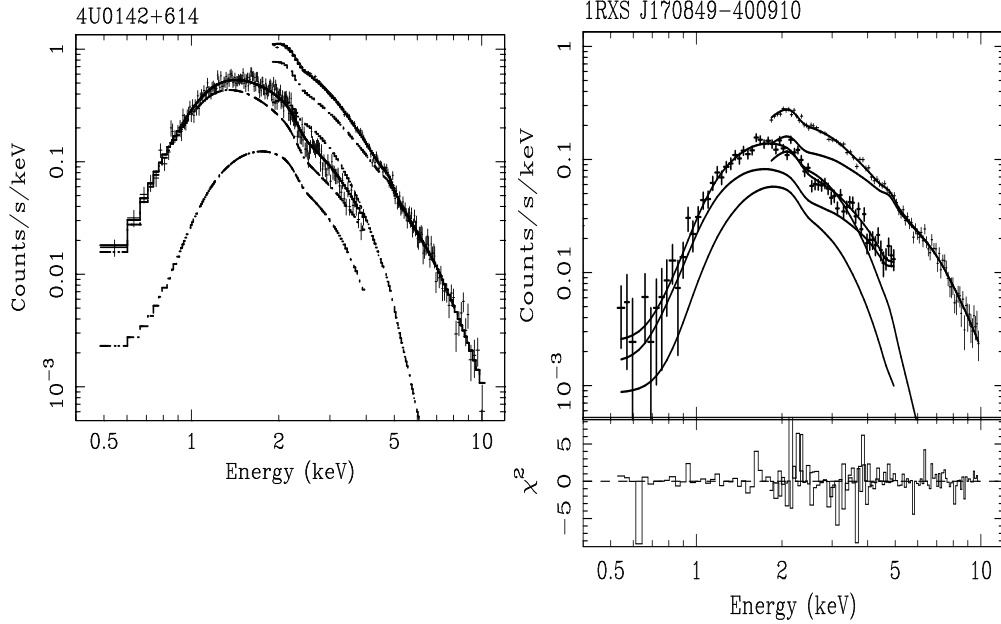


Fig. 1. LECS and MECS energy spectra of two AXPs, 4U 0142+614 (left; adapted from Israel et al. 1999) and 1RXS J170849–400910 (right). For the latter source the residuals (in units of χ^2) of the best fit are also shown. The power-law and blackbody components are also shown.

a blackbody component with a characteristic temperature of 0.45 ± 0.03 keV (90% c.l. reported; Israel et al. 2001a). The unabsorbed 1–10 keV flux was $6 \times 10^{-11} \text{ erg s}^{-1}$. The blackbody component accounts for about 30% of the total observed flux. Figure 1 compares the spectral shape and components of 1RXS J170849–400910 and 4U 0142+614 as seen by *BeppoSAX*. 1RXS J170849–400910 is therefore the fourth AXP for which a two component spectrum (steep power-law plus soft blackbody) has been detected.

A further interesting result of the 1RXS J170849–400910 *BeppoSAX* observation was the detection of a clear pulse shape change as a function of energy (see left panels of Figure 2). In particular the minimum in the lowest energy interval (0.1–2 keV) corresponds to a maximum in the 6–10 keV band. The pulsed fraction (semiamplitude of modulation divided by the mean source count rate) decreases from 40% to 30% from the lowest to the highest energy band, respectively. Pulse phase spectroscopy was carried out with the MECS data (due to poor statistics at low energies the data from the LECS data were not used). By keeping the parameters of the blackbody component fixed at the phase-averaged value, a $\sim 3\sigma$ significant variation in the power-law photon index was found. The large uncertainties prevent the detection of possible variations in N_H (see right panels of Figure 2). Although small energy-dependent changes in the pulse shape were already suggested in the past for 4U 0142+614 (Israel et al. 1999a; Paul et al. 2000), the variations of 1RXS J170849–400910 are highly significant and likely arising from a changing power-law slope. The lack of any conspicuous change in the pulse

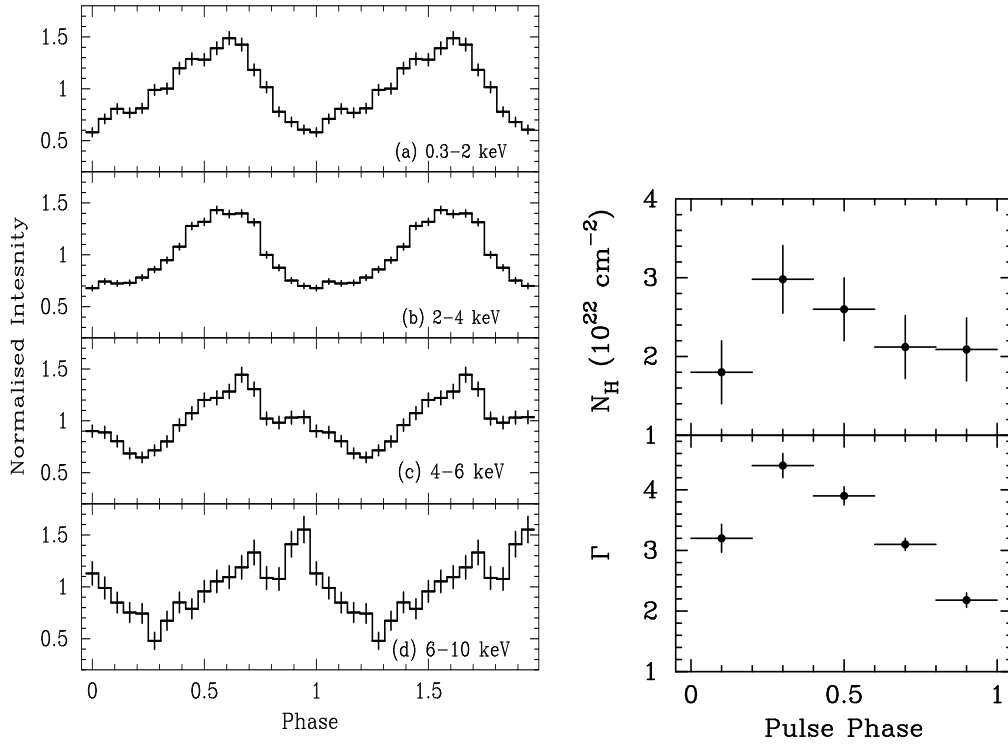


Fig. 2. 1RXSJ170849–400910 MECS and LECS light curves folded to the best period ($P=10.99915$ s) for four different energy intervals (left panels). For clarity two pulse cycles are shown. Zero phase was (arbitrarily) chosen to correspond to the minimum in the 0.3–2 keV folded light curve. The results of the pulse phase spectroscopy are also reported for the two free spectral parameters (right panels).

profiles of AXPs was used in the past to argue against the possibility that these sources are accreting X-ray objects. More sensitive studies will yield additional information on the spectral changes causing the pulse shape variations, extend the energy range of the source detection above 10 keV, and allow to look for cyclotron signatures.

The spectral properties of 1RXSJ170849–400910 reported above are plotted in Figure 3 (left panels) together with the *BeppoSAX* results obtained for the other three AXPs for which good spectral data are available. It is apparent that the spectral properties of AXPs are relatively homogeneous. 1E 1048.1–5937 has the highest blackbody temperature and largest (absorbed) $L_{BB}/L_{tot\,abs}$ ratio. Note that the $L_{BB}/L_{tot\,abs}$ ratio is not strongly dependent on the power-law photon index. The AXPs with the largest (1RXSJ170849–400910) and smallest (1E 1048.1–5937) absorption have nearly the same photon index, suggesting that the detection of a steep power-law in AXPs is not an artifact due to a large N_H value.

The picture becomes quite different when extrapolating the total unabsorbed fluxes

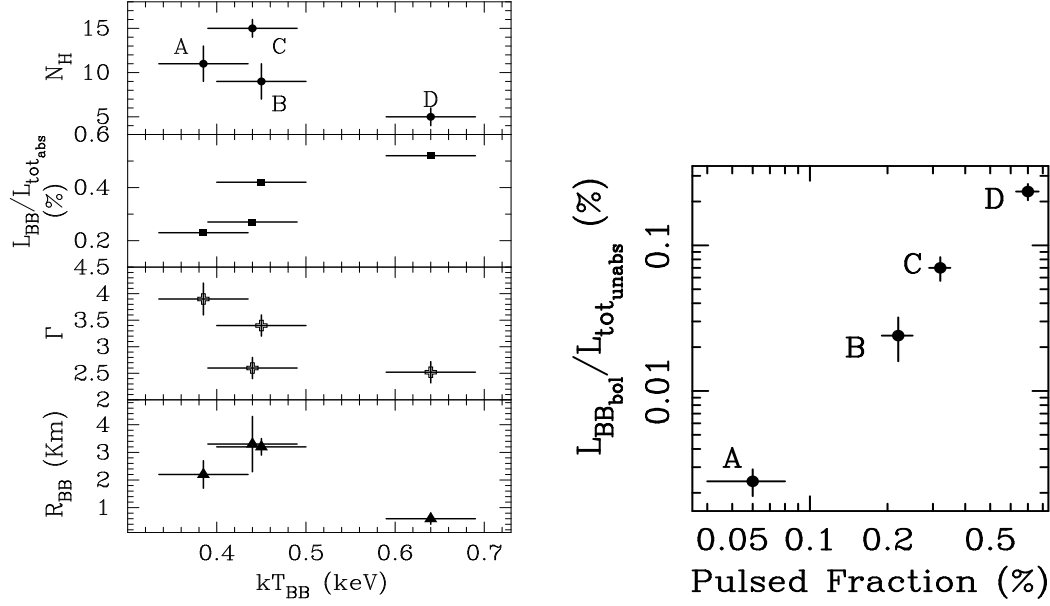


Fig. 3. The main spectral properties of AXPs (A=4U 0142+614, B=1E 2259+586, C=1RXS J170849–400910 and D=1E 1048.1–5937) observed by *BeppoSAX* are reported as a function of the characteristic blackbody temperature (left panels). Error bars in the blackbody radius reflects also the uncertainty in the assumed distances. Absorption column values are in units of 10^{21} cm^{-2} . The correlation between AXP pulsed fractions and the bolometric $L_{BB_{bol}}$ and the total unabsorbed 0.1–10 keV luminosity $L_{tot_{unabs}}$ ratio is also shown (right panel).

in the 0.1–10 keV range and considering the bolometric blackbody flux; this gives in all cases a $L_{BB_{bol}}/L_{tot_{unabs}}$ ratio smaller than 30%. Despite the $\sim 10^3$ ratio in total unabsorbed flux between the brightest (4U 0142+614) and faintest (1RXS J170849–400910) AXPs, the blackbody component varies by only a factor of ~ 10 , strongly suggesting that the energy budget of AXPs is largely dominated by the power-law. Another interesting result is shown in the right panel of Figure 3 where the 0.1–10 keV pulsed fractions are plotted as a function of $L_{BB_{bol}}/L_{tot_{unabs}}$. This correlation strongly suggests that the thermal component is mainly responsible for the pulsations component. This is also in agreement with the fact that 4U 0142+614, the brightest AXP, has also the lowest known pulsed fraction (Israel et al. 2001b).

5. Further X-ray observations

Several results from X-ray observations of AXPs and related objects were reported in the last year. In particular the pulsation stability of AXPs was compared to that of conventional accreting X-ray pulsars and isolated radio pulsars. 1RXS J170849–400910 and 1E 2259+586 were the first two AXPs for which a systematic study was carried out

and phase-coherent timing solutions obtained by means of *RossixTE* data (Kaspi et al. 1999). These two sources were found to be quite stable rotators with phase residuals of only $\sim 1\%$, comparable to or smaller than those measured for most radio pulsars. However, in September 1999 the *RossixTE* satellite detected a sudden spin-up event in 1RXS J170849–400910 which was originally interpreted as a “glitch” similar to that observed in the Vela and other young radio pulsars (Kaspi et al. 2000a). However, we note that in principle glitches could also be detected in accreting spinning-down X-ray sources (with a sufficiently high magnetic field strength) if they are in a low noise level phase, as indeed AXPs are known to be. A way to distinguish, in the near future, whether 1RXS J170849–400910 experienced a radio pulsar-like glitch or, perhaps, an accreting X-ray pulsar-like spin-up behaviour would be to accurately monitor the period history after the event. Unfortunately these results have not been reported so far.

Also the pulsations stability of 1E 1048.1–5937 was studied in great detail with ASCA (Paul et al. 2000) and *RossixTE* (Kaspi et al. 2000b) data. In the latter case the sampling proved insufficient to find a phase-coherent solution due to a high noise level (changing spin-down rate). The observed deviations from simple spin-down were found to be inconsistent with a single glitch event. Such period changes do not seem to be accompanied by pulse shape or spectral changes (in ASCA) or even flux variations as observed in accreting X-ray pulsars (Paul et al. 2000; Kaspi et al. 2000b). In this respect 1E 1048.1–5937 was suggested to be a transition object between SGRs and AXPs (Kaspi et al. 2000b). Based on earlier *RossixTE* data, Baykal et al. (2000a) found that the level of pulse fluctuations in 1E 1048.1–5937 is consistent with the typical noise level of accretion powered pulsars (Baykal & Ögelman 1993; Bildsten et al. 1997). Also the results of further *RossixTE* observations of 1E 2259+586 suggest that the source is perhaps in a fairly stable accretion phase with a constant X-ray luminosity and spin-down rate (Baykal et al. 2000a). An interesting result has been recently reported for the high-mass accreting X-ray pulsar 4U 1907+09. This is the only known X-ray pulsar (besides AXPs) which has always been spinning-down since the discovery of pulsations at 440 s in its X-ray flux in 1983. This result, based again on *RossixTE* data, shows that 4U 1907+09 during 1996–1998 has been a rather stable rotator with a spin-down rate only a factor four greater than that of 1E 2259+586 (Baykal et al. 2000b). Furthermore the long-term noise strength of 4U 1907+09 is one order of magnitude lower than that of 1E 2259+586; the conclusion is that the existence of an accreting source displaying persistent spin-down shows that quiet spin-down trends do not necessarily imply that the sources are not accreting.

No new results have been reported concerning the search of orbital signatures by means of delays in the pulse arrival times of AXPs. In fact after the tight upper limits inferred on the possible companion star mass of 1E 1048.1–5937 and 1E 2259+586 (Mereghetti et al. 1998), and 4U 0142+614 (Wilson et al. 1999) based on *RossixTE* data, none of the other three AXPs has been studied in this respect. The lack of detectable Doppler effect has been used by many authors to favor the magnetar scenarios. It is worth mentioning that the pulse arrival time delays remain undetected also in 4U 1626–674, an X-ray pulsar with a very low-mass companion star (likely a light He-burning or He white dwarf; see Chakrabarty 1998) in a 42 min orbital period binary. If AXPs were in binary systems with companion stars similar to that of 4U 1626–674, expected

delays would be below the current upper limits.

Finally Marsden & White (2001) recently found a correlation between spin-down rates of AXPs and SGRs and the $L_{\text{BBbol}}/L_{\text{PL}}$ ratio concluding that, regardless the nature of these sources, they are likely objects with similar emission mechanisms.

6. Optical/IR follow-up observations

Similar to other Galactic X-ray sources, the identification of AXPs at optical and IR wavelengths suffers from the comparatively poor spatial resolution of X-ray telescopes which is often inadequate to cope with the crowded Galactic plane fields in which AXPs lie, and the strong extinction in their direction. Although the X-ray positional accuracy is not yet sufficient to unambiguously identify the possible optical/IR counterparts of AXPs, it is now possible to sort out a number of good candidates or, at least, put tight constraints on the optical/IR-to-X-ray energy distribution of these sources.

This is the case of the recent proposed optical counterpart of 4U 0142+614, a faint relatively blue object ($R=25$; $V - R=0.63$) which, in the color-magnitude diagram, lies half-way between the main sequence and the track of $0.6 M_{\odot}$ white dwarfs (Hulleman et al. 2000a; Keck observations). However the optical counterpart candidate position of 4U 0142+614 (within the Einstein HRI error circle; White et al. 1987) is outside the EXOSAT LEIT error circle (White et al. 1987) and at the edge of the ROSAT PSPC one. A more accurate X-ray position is clearly needed in order to confirm this result. Since none of the accretion-based scenarios considered by Hulleman et al. (2000a) fit the optical and X-ray data these authors conclude that the measurements may be in agreement with a magnetar. However no detailed models have yet been developed for the optical emission of magnetars (Hulleman et al. 2000a). We note that the optical data are also in agreement with at least two other scenarios: (a) a binary system hosting a white dwarf companion, which accounts for the optical emission, and an accreting neutron star producing the X-ray emission, (b) a disk around an isolated NS with a more realistic choice of values for the disk size, illumination and inclination (Israel et al. 2001c).

Hulleman et al. (2000b) carried out also a relatively deep search for the optical counterpart of 1E 2259+586 based on Keck observations. No object was found down to limiting magnitudes of $R=25.7$ and $I=24.3$. These authors conclude that it is unlikely that 1E 2259+586 is an isolated NS accreting from a residual disk. Also in this case, however a binary system with a helium-burning $0.3 M_{\odot}$ or a white dwarf companion star, or a magnetar scenario cannot be excluded yet.

Optical observations of the field of 1RXS J170849–400910 were obtained by Israel et al. (1999b). These authors found that the possible counterpart cannot be a massive early type star (a distant and/or absorbed OB star would appear more reddened). However the images were taken from a 1.5 m telescope and are not deep enough to constrain any other proposed theoretical scenario such as a low mass companion, a residual disk or a magnetar.

Recently Mereghetti et al. (2001) reported on the first search for optical/IR counterpart in the field of 1E 1841–045 located at the center of the SNR Kes 73 (mainly with the 1.5 m and 3.5 m class ESO telescopes). Similar to the previous case, the results are not very constraining, due to the high extinction in the direction of the source ($A_V \geq 11$). No

Tab. 2 - Current Optical/IR upper limits and measurements

SOURCE	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>	<i>J</i>	<i>K</i>	Ref.
1E 1048.1–5937	>24.5	>24.5	>24.3	—	—	—	[1]
1E 2259+586	>25	>24	>25.7	>24.3	>19.6	>18.4	[2,3]
4U 0142+614	—	25.6	25	25	>19.6	>16.9	[4,3]
RXSJ170849–4009	>20	>25	>26.4	>25	—	—	[5,6]
1E 1841–045	>23	>22	>24	—	>19	>17	[7]

Note: Values are taken from [1] Mereghetti et al. 1992, [2] Hulleman et al. 2000b, [3] Coe & Pightling 1998, [4] Hulleman et al. 2000a, [5] Israel et al. 1999b, [6] Israel et al. 2001a, [7] Mereghetti et al. 2001.

detailed reports on optical/IR observations of AX J1844–0258 have yet been published. Table 2 summarises the current optical/IR upper limits and measurements of AXPs.

7. Radio follow-up

If AXPs are isolated NSs that emit radiation in a fashion similar to rotation powered pulsars then they might shine and pulsate also in the radio band. We observed the fields of four southern AXPs, namely 1E 1048.1–5937, 1E 1841–045, AX J1844–0258 and 1RXS J170849–400910, with the Parkes Observatory and typical exposures of 10–20 ks for each source. The sampling time was in the 1–1.2 ms range with a beam aperture of $\sim 14'$ (at 1.4 GHz). Sampled duty cycles were in the ~ 0.001 –20% range, while dispersion measures (DM) up to 10 times larger than the Galactic values in the direction of observed AXPs were sampled in order to take into account also the possible presence of local matter. Setting the detection threshold at a signal to noise ratio of 10, an average value of $\sim 70 \mu\text{Jy}$ at 1.4 GHz can be reasonably assumed for the upper limit to the radio flux of the sample of observed AXPs observed. The search for coherent signals at the X-ray period (we used the P and \dot{P} values reported in Table 1 to infer the period interval for the search) did not detect any significant signal (Burderi et al. 2001).

8. The Future

After more than 20 years from the discovery of pulsations from 1E 2259+586 the nature of AXPs is still uncertain. Important limiting factors in the study of AXPs are: (i) the relatively low X-ray positional accuracy provided so far by X-ray telescopes together with the difficulties in obtaining deep optical/IR images (needed to sample faint objects) from the largest ground-based telescopes, (ii) the lack of spectral information above 10 keV where many cosmic X-ray sources (X-ray pulsars especially) display important features, (iii) the paucity of unambiguous predictions by theoretical models, and (iv) the small numbers in the currently known AXP population. The present generation of X-ray astronomy satellites (Chandra and *Newton*XMM) and large ground-based telescopes (VLT, Gemini, Subaru and KeckII) opens new perspectives in the field. The unrivalled spatial resolution and absolute source positioning accuracy ($\leq 1''$) of Chandra will provide the best chance to unambiguously identify the counterparts of AXPs. Moreover assessing that the AXP candidate AX J1844–0258 (which has shown a factor of

variability larger than 10) is indeed an AXP would imply that the number of AXPs and their formation rate have been largely underestimated. The high throughput of *Newton*XMM and the relatively wide field of view of its instruments will presumably allow to find other AXPs even at fainter fluxes, thus providing new important informations to understand the puzzling nature of AXPs.

Acknowledgements

The results reported in this review have been obtained with the contribution of a number of scientists, who are part of large international collaboration aimed at studying the AXPs. It is a pleasure to thank all the people who have contributed to this project: L. Angelini, L. Burderi, S. Campana, S. Covino, N. D’Amico, F. Haberl, G. Marconi, R. Mignani, I. Negueruela, T. Oosterbroek, A.N. Parmar, A. Possenti, and N.E. White.

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